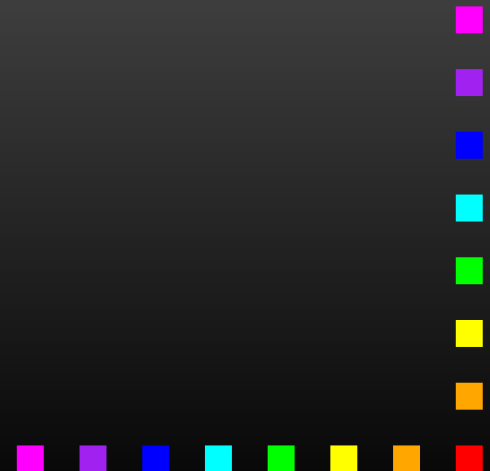


Precision Higgs Masses with FeynHiggs 2.2

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Motivation

Arguably the most important task of the LHC is to

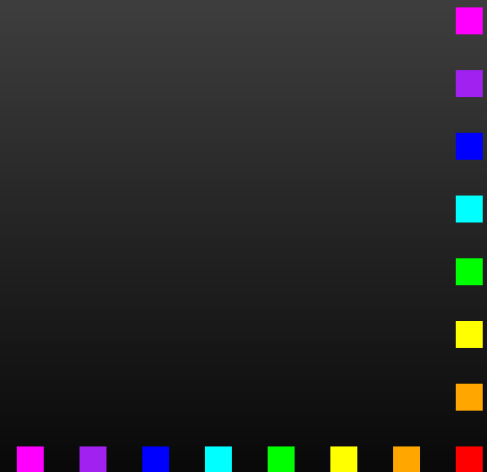
- find a Higgs boson and, if it exists,
- measure its properties to distinguish different models.

Necessary on the theory side: precise predictions of

- masses, couplings, branching ratios, . . .

in a variety of models

- SM,
- real MSSM,
- complex MSSM,
- non-minimal flavour-violating MSSM,
- NMSSM . . .



The MSSM Higgs Sector

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 + i\chi_1) \\ \phi_1^- \end{pmatrix}, \quad H_2 = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

Higgs Potential:

$$V = M_1^2 H_1 \bar{H}_1 + M_2^2 H_2 \bar{H}_2 - M_{12}^2 (\varepsilon_{\alpha\beta} H_1^\alpha H_2^\beta + \text{h.c.}) + \frac{g_1^2 + g_2^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g_2^2}{2} |H_1 \bar{H}_2|^2$$

- **Five physical states, h^0 , H^0 , A^0 , $H^\pm$ (no ~~CP~~ at tree level).**
- **Input parameters:** $\tan \beta = v_1/v_2$, M_{A^0} or $M_{H^\pm}$.
- **Unlike SM, MSSM predicts M_{h^0} (cf. Gauge Couplings).**
- **$M_{h^0} < M_Z$ at tree level, excluded by LEP searches.**

Radiative Corrections

Significant quantitative and qualitative changes:

- M_{h^0} receives large radiative corrections, e.g. the dominant one-loop corrections $\sim G_F m_t^4 \log(M_{\tilde{t}_1} M_{\tilde{t}_2} / m_t^2)$.
- The MSSM Higgs sector is connected to all others (in particular the scalar top sector) by loop corrections.
- ~~CP~~ parameters lead to self-energies $\hat{\Sigma}_{hA}, \hat{\Sigma}_{HA} \neq 0$ and induce mixing between h^0 , H^0 and A^0 :

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} h^0 \\ H^0 \\ A^0 \end{pmatrix}$$

Real MSSM (rMSSM)

- “Unconstrained (real) MSSM” has M_{A^0} , $\tan \beta$, **5 parameters in $\tilde{t}$ - $\tilde{b}$ sector**, μ , $m_{\tilde{g}}$, M_2 .

- $M_{h^0} \lesssim 135 \text{ GeV}$ for $m_t = 175 \text{ GeV}$.

Heinemeyer, Hollik, Weiglein 1999

Degrassi, Heinemeyer, Hollik, Slavich, Weiglein 2002

- **Complete one-loop result + all presumably dominant two-loop corrections known.**

- **Remaining uncertainties:**

From unknown higher-order corrections: $\Delta M_{h^0} \approx 3 \text{ GeV}$.

From input-parameter uncertainties: $\Delta M_{h^0} \approx 4 \text{ GeV}$ for $\Delta m_t \approx 4 \text{ GeV}$.

Degrassi, Heinemeyer, Hollik, Slavich, Weiglein 2002

Frank, Heinemeyer, Hollik, Weiglein 2002

Allanach, Djouadi, Kneur, Porod, Slavich 2004



Complex MSSM (cMSSM)

- Complex parameters enter via loop corrections and can induce ~~CP~~ effects: $\mu, M_{1,2}, m_{\tilde{g}}, A_{t,b,\tau}$.
- Known:
 - ▷ fermion/sfermion one-loop corrections,
 - ▷ some leading logs from remaining sectors,
 - ▷ leading two-loop corrections.

Pilaftsis 1999 – Pilaftsis, Wagner 1999 – Demir 1999 – Choi, Drees, Lee 2000 – Heinemeyer 2001
Carena, Ellis, Pilaftsis, Wagner 2000, 01 – Ibrahim, Nath 2001, 02 – Ham, Kim, Oh, Son, Yoo 2002

- Previously unknown:
 - ▷ remaining sectors at one loop (5 GeV in rMSSM),
 - ▷ q^2 dependence at one loop (~ 2 GeV in rMSSM).
- Much larger uncertainties than in the rMSSM.

Corrections included in FeynHiggs 2.2

$$\begin{pmatrix} q^2 - M_h^2 + \hat{\Sigma}_{hh}^{\bullet\bullet\bullet} & \hat{\Sigma}_{hH}^{\bullet\bullet\bullet} & \hat{\Sigma}_{hA}^{\bullet\bullet\bullet} \\ \hat{\Sigma}_{Hh}^{\bullet\bullet\bullet} & q^2 - M_H^2 + \hat{\Sigma}_{HH}^{\bullet\bullet\bullet} & \hat{\Sigma}_{HA}^{\bullet\bullet\bullet} \\ \hat{\Sigma}_{Ah}^{\bullet\bullet\bullet} & \hat{\Sigma}_{AH}^{\bullet\bullet\bullet} & q^2 - M_A^2 + \hat{\Sigma}_{AA}^{\bullet\bullet\bullet} \end{pmatrix}$$

- **Most up-to-date leading $\mathcal{O}(\alpha_s\alpha_t, \alpha_t^2)$ + subleading $\mathcal{O}(\alpha_s\alpha_b, \alpha_t\alpha_b, \alpha_b^2)$ two-loop corrections in the rMSSM (complex effects only partially included in two-loop part).**

Degrassi, Slavich, Zwirner 2001 – Brignole, Degrassi, Slavich, Zwirner 2001, 02

Dedes, Degrassi, Slavich 2003

- **Full one-loop evaluation (all phases included).**
- **Complete q^2 dependence.**
- **Full one-loop corrections for the charged Higgs sector.**

Frank, Heinemeyer, Hollik, Weiglein 2002

Additional Features

- **New renormalization ($\overline{\text{MS}}/\text{OS}$)** for one-loop result.

Frank, Heinemeyer, Hollik, Weiglein 2002

- **“ Δm_b ” corrections** = leading $\mathcal{O}(\alpha_s \alpha_b)$ terms for Higgs masses, couplings, etc.

Carena, Garcia, Nierste, Wagner 2000

- **Non-minimal flavour-violating effects** (e.g. $\tilde{c}-\tilde{t}$ mixing).

Heinemeyer, Hollik, Merz, Peñaranda 2004

- **$\Delta\rho$ at $\mathcal{O}(\alpha, \alpha\alpha_s)$** as an additional constraint.

$\Delta\rho \gtrsim 2 \times 10^{-3}$ indicates exp. disfavoured $\tilde{t}/\tilde{b}$ masses.

- **$(g_\mu - 2)_{\text{SUSY}}$** as an additional constraint.

Full one-, leading/subleading two-loop SUSY corrections.

Heinemeyer, Stöckinger, Weiglein 2003



Output of FeynHiggs 2.2

- **FHHiggsCorr:** All Higgs-boson masses and mixings:
 $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}, \alpha_{\text{eff}}, U_{ij}, \dots$

- **FHCouplings:**

- ▷ **Couplings and Branching Ratios for the channels**

$h_{1,2,3} \rightarrow f\bar{f}, \gamma\gamma, ZZ^*, WW^*, gg$	$H^\pm \rightarrow f\bar{f}'$
$h_i Z^*, h_i h_j, H^+ H^-$	$h_i W^{\pm*}$
$\tilde{f}_i \tilde{f}_j$	$\tilde{f}_i \tilde{f}'_j$
$\tilde{\chi}_i^\pm \tilde{\chi}_j^\pm, \tilde{\chi}_i^0 \tilde{\chi}_j^0$	$\tilde{\chi}_i^0 \tilde{\chi}_j^\pm$

- ▷ **Branching Ratios of an SM Higgs with mass M_{h_i} :**

$$h_{1,2,3}^{\text{SM}} \rightarrow f\bar{f}, \gamma\gamma, ZZ^*, WW^*, gg$$

- **FHConstraints:** Additional constraints $\Delta\rho, (g_\mu - 2)_{\text{SUSY}}$

Download and Build

- Get **FeynHiggs-2.2beta.tar.gz** from **www.feynhiggs.de**.
- Unpack and configure:

```
tar xvfz FeynHiggs-2.2beta.tar.gz  
cd FeynHiggs-2.2beta  
./configure
```
- Type **make** to build the Fortran/C++ part only.
Type **make all** to build also the Mathematica part.
Takes about 2 min to build on a Pentium IV.
- Type **make install** to install the package.
- Type **make distclean** to remove unnecessary files.

Note: no prerequisites (e.g. LoopTools) required as in previous versions.

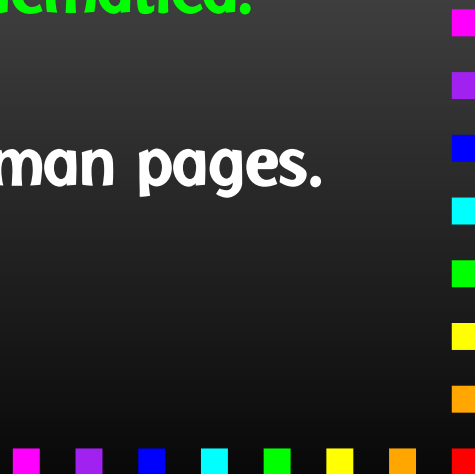


Usage

Three operation modes:

- **Library Mode:** Invocation from Fortran or C++ program, linked against the `libFH.a` library.
- **Command-line Mode:** Standalone executable `FeynHiggs` reads parameter file in FeynHiggs or SLHA format and writes out the results.
- **Mathematica Mode:** MathLink executable `MFeynHiggs` makes FeynHiggs routines accessible in Mathematica.

All programs and subroutines are documented in man pages.



Library Mode

Subroutines contained in FeynHiggs 2.2:

- **FHSetFlags** - set the flags of the calculation,
- **FHSetPara** - set the **MSSM** input parameters directly, *or*:
FHSetSLHA - extract the input parameters from an SLHA data structure,
- **FHGetPara** - retrieve (some of) the derived parameters (e.g. chargino masses),
- **FHHiggsCorr** - compute the Higgs masses and mixings,
- **FHCouplings** - compute the Higgs couplings and BRs,
- **FHConstraints** - evaluate $\Delta\rho$ and $(g_\mu - 2)$ constraints.

C++ users need to include `CFeynHiggs.h` for prototypes.

Couplings

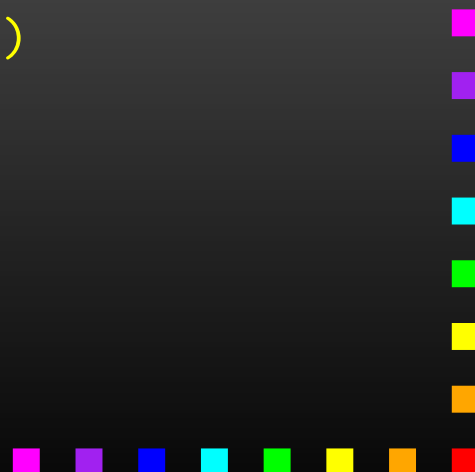
Internal software engineering straightened out,
e.g. access to couplings much simplified:

```
#include "FHCouplings.h"
```

```
double precision couplings(ncouplings)
double precision gammas(ngammas)
double precision gammasms(ngammasms)
...
```

```
call FHCouplings(couplings, gammas, gammasms)
```

```
br_hZZ = BR(H0VV(1,3))
lcpl_Htt = LCoupling(H0FF(2,3,3))
rcpl_Htt = RCoupling(H0FF(2,3,3))
...
```



Command-line Mode

Input File

MT	178
MB	4.7
MW	80.450
MZ	91.1875
MSusy	975
MA0	200
Abs(M_2)	332
Abs(MUE)	980
TB	50
Abs(At)	-300
Abs(Ab)	1500
Abs(M_3)	975

Command
FeynHiggs file flags

Screen Output

```
----- HIGGS MASSES -----
| Mh0    = 116.022817
| MHH    = 199.943497
| MA0    = 200.000000
| MHP    = 216.973920
| SAeff  = -0.02685112
| UHiggs = 0.99999346  -0.00361740  0.00000000 \
|         0.00361740  0.99999346  0.00000000 \
|         0.00000000  0.00000000  1.00000000
-----
----- DECAY WIDTHS AND BRANCHING RATIOS -----
| GammaTot-h0    = 0.448747E-02
| GammaTot-HH    = 4.71901
| GammaTot-A0    = 4.73148
| GammaTot-Hp    = 1.24126
| ...
```

- Loops over parameter values possible (parameter scans).
- Mask off details with `FeynHiggs file flags | grep -v %`
- `table` utility converts to machine-readable format, e.g.
`FeynHiggs file flags | table TB Mh0 > outfile`

SUSY Les Houches Accord Format

Input File

BLOCK MODSEL

1 1

BLOCK MINPAR

1 0.100000000E+03 # m0
2 0.250000000E+03 # m12
3 0.100000000E+02 # tanb
4 0.100000000E+01 # Sign(mu)
5 -0.100000000E+03 # A0

BLOCK SMINPUTS

4 0.911870000E+02 # MZ
5 0.425000000E+01 # mb(mb)
6 0.175000000E+03 # t

...

Command

FeynHiggs *file flags*

file.fh

BLOCK MASS

25 1.12697840E+02 # Mh0
35 4.00145460E+02 # MHH
36 3.99769788E+02 # MA0
37 4.08050556E+02 # MHp

...

BLOCK ALPHA

-1.10658125E-01 # Alpha

...

- **{ Uses / was developed into }** the SLHA I/O Library.

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- **SLHA** can also be used in Library Mode with FHSetSLHA.
- **FeynHiggs** tries to read each file in SLHA format first.
If that fails, fallback to native format.

Mathematica Mode

Provides the FeynHiggs functions in Mathematica, e.g.

```
In[1]:= Install["MFeynHiggs"];
```

```
In[2]:= FHSetFlags[...];
```

```
In[3]:= FHSetPara[...];
```

```
In[4]:= FHHiggsCorr[]
```

```
Out[4]= {MHiggs -> {117.184, 194.268, 200., 212.67},  
>      SAeff -> -0.37575,  
>      UHiggs -> {{0.994782, 0.102021, 0},  
>                  {-0.102021, 0.994782, 0},  
>                  {0, 0, 1.}}}
```

- Can use all Mathematica functions on the results (e.g. ContourPlot, FindMinimum).
- Convenient interactive mode for FeynHiggs 2.2.

Spin-Off: SLHA I/O Library

- The SUSY Les Houches Accord defines a common interface for SUSY tools.

Skands et al. 2003

- Reading/writing SLHA files not entirely straightforward.
- The SLHA I/O Library fills this gap:
 - ▷ Implemented as **native Fortran-77 Library**.
 - ▷ All data transferred in **one double-precision array**.
 - ▷ This array is **indexed by preprocessor macros**, e.g. `MinPar_TB` instead of `slhadata(20)`.
 - ▷ **Main functions:** `SLHARead`, `SLHAWrite`.

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- Freely available at **<http://www.feynarts.de/SLHA>**.



Summary

- FeynHiggs 2.2 provides **Higgs-boson masses, couplings, branching ratios, etc. in the real or complex MSSM.**
- Full one-loop evaluation including q^2 dependence.
- Latest leading and subleading two-loop corrections.
Inclusion of complex phases at two loop in preparation.
- Easy to build. Three operating modes:
Library Mode, Command-line Mode, Mathematica Mode.
- Command-line Mode reads **files in native or SLHA format.**
- Download from <http://www.feynhiggs.de>.
Maintained by S. Heinemeyer and T. Hahn.
- Spin-off: **SLHA I/O Library.**
Download from <http://www.feynarts.de/SLHA>.

